Improved detection of large cirrus particles from infrared spectral observations

Ashwin Mahesh

Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, USA

NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Received 3 October 2003; revised 10 November 2003; accepted 18 December 2003; published 26 February 2004.

[1] Spectral observations of cirrus clouds can be analyzed to obtain cloud particle effective radii using measurements at select wavenumbers in the infrared atmospheric window. The suitability of these wavenumbers to determine a range of sizes is constrained by the dependence on particle radius of ice absorption efficiency (Q_{abs}). By using only those wavenumbers at which Q_{abs} varies monotonically with radius, cloud particle radii up to approximately 20 μm can be determined; larger values, however, present problems. At some wavenumbers, the variation in Q_{abs} is not sufficiently large to distinguish between large particle radii. At other wavenumbers, larger particles are more easily distinguished, but Q_{abs} values do not correspond to unique particle radii. Using one set of wavenumbers only to determine whether the particle is large or small, and a second set to actually determine the effective radius of a large cloud particle, the limitations faced at individual wavenumbers can be partially overcome. This is demonstrated using yearlong spectral observations of ice clouds at South Pole station. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Mahesh, A. (2004), Improved detection of large cirrus particles from infrared spectral observations, *Geophys. Res. Lett.*, *31*, L04110, doi:10.1029/2003GL018768.

1. Introduction

[2] Ground-based observations of ice clouds from moderate- and high-resolution spectrometers are now available from a few polar observation programs [e.g., *Walden et al.*, 1998; *Perovich et al.*, 1999], and radiance measurements from these have been analyzed to obtain cloud effective particle radii. Spectral data are also taken routinely at the North Slope of Alaska site of the Atmospheric Radiation Measurement program [*Zak and Stamnes*, 1992], and similar observations of cirrus have also been made during multi-instrument field campaigns. In comparison the to typical 5-channel observations from the Advanced Very High Resolution Radiometers (AVHRR) on National Oceanic and Atmospheric Administration (NOAA) satellites, or even the 36-band observations of the Moderate Resolution Imaging Spectroradiometers [*King et al.*, 1992] on board more recent missions, these spectral data represent a significant improvement. The accuracy of cloud microphysical and radiative properties obtained from spectral measurements is keenly dependent on the specific wavelengths of observation; newer instruments are designed to make observations at increasingly higher resolution. As a result, scientists have been able to obtain cloud particle radii and optical depths to greater accuracy than with MODIS and AVHRR data, which rely on approximations of the ideal observing wavenumbers.

2. Improved Determination of Particle Effective Radius

[3] The vastly greater number of channels at which data is collected by high-resolution spectral instruments (typically, every 0.5 cm^{-1}) allows the selective use of channels most sensitive to cloud microphysical properties at particular heights in the atmosphere. Analysis techniques typically exploit the variation in ice absorption between 800 and 1200 cm^{-1} in the infrared atmospheric window - between the 15-μm carbon-dioxide absorption band and the 9.6-μm ozone emission band. At each spectral interval of observation, radiances obtained from measurements can be compared with values calculated for different combinations of cloud particle radii and optical depths, and the pair representing the minimum difference between observation and calculation is determined. Increased availability of spectral channels, therefore, makes the true minimum more likely to be determined through such analysis. Also, when channels close to the ideal wavenumbers (at which the sensitivity to microphysical properties is greatest) are available, the use of other channels that contain less useful information can be reduced or avoided altogether.

[4] Figure 1 shows the variation of absorption efficiency (Q_{abs}) with particle size, calculated using Mie theory for ice spheres at different infrared atmospheric 'micro-windows'. At most wavenumbers shown, Q_{abs} is most useful in determining small particle sizes; the variability in Q_{abs} values is much smaller for larger particles. Secondly, the curves are not always monotonic. At each wavenumber, Q_{abs} increases with particle radius and reaches a peak at some radius, and reverses sign with further increases in particle size. Moreover, this 'limit of monotonic detection' itself increases with wavenumber, as shown in Figure 2. This figure shows the maximum particle radius that can be detected from monotonic changes in Q_{abs} values (left axis, solid curve) as well as the variation in Q_{abs} for larger particles (20 to 50 μm) at several wavenumbers. Although at larger wavenumbers, it is possible to detect bigger particles, Q_{abs}

0094-8276/04/2003GL018768$05.00

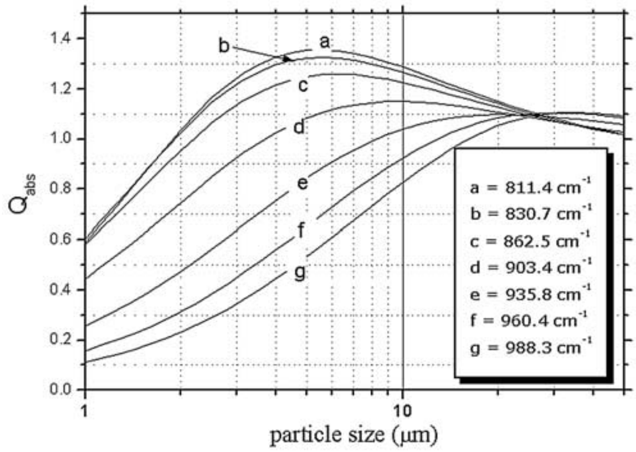

Figure 1. Absorption efficiencies at wavenumbers across the infrared atmospheric window. Sensitivity to particle size is seen at all wavenumbers, but at smaller wavenumbers, absorption efficiencies do not correspond to unique particle radii. At larger wavenumbers, variation in efficiency with particle radius is not seen beyond approximately 20 μm.

values are not as variable as at smaller wavenumbers; this limits the reliability of large particle radii determined using larger wavenumbers.

[5] To detect effective particle radii from observations in the atmospheric window, therefore, requires two critical factors. First, Q_{abs} values must vary sufficiently with particle size over a range of radii, and second, such variation must be monotonic to obtain unique values of particle size over the range. Many analysis techniques also use a reference wavenumber at which the two are balanced, and select detection wavenumbers to have clearly different absorption efficiencies from this reference. *Mahesh et al.* [2001], for example, conducted their analysis of cirrus clouds over South Pole using 903 cm^{-1} as the reference wavenumber and 988 cm^{-1} as the wavenumber of detection; at the larger value Q_{abs} rises monotonically over a large range of particle radii, and for much of that range its variability is sufficient to distinguish sizes.

[6] Figure 2, nonetheless, suggest that the detection of larger particles may be possible using smaller wavenumbers, provided the non-uniqueness of particle size values that would be obtained using these frequencies can be overcome. Because the limit of monotonic detection is typically smaller than 10 μm at smaller wavenumbers, however, we cannot use these spectral micro-windows to detect small particles. On the descending portion of Q_{abs} curves (in Figure 1) at small wavenumbers, however, variability in Q_{abs} is both monotonic and sufficiently large. Therefore, we only need to rule out the possibility that the particle radius is small, say, less than 10–15 μm. Once that determination has been made, we can thereafter turn to using a smaller wavenumber (e.g., 811 cm^{-1}) as more suited to observations of larger particles, and to distinguish between them in size. At 811 cm^{-1} the variability in Q_{abs} values for particle radii between 20 and 50 μm is seven or eight times the corresponding variability at 988 cm^{-1}; the former is better suited to detecting large particle sizes once it is determined that the particles are in fact large; without this assurance the Q_{abs} values cannot be uniquely attributed to large particles.

[7] This improved detection of larger particles, however, does not eliminate earlier uncertainties in particle size that result from uncertainties in the radiance measurements themselves. At the limit of size detection, variability in absorption efficiency is small; *Mahesh et al.* [2001, Figure 13] showed the effects of nearly unchanging Q_{abs} values, and those limitations continue to apply even with the improved method outlined here. However, the Q_{abs} curves (Figure 1) suggest that at the same degree of uncertainty previously available to detect particles between 15 and 25 μm using larger wavenumbers, it should be possible to detect particle sizes up to 30 or 35 μm using smaller wavenumbers instead; this similarity of uncertainties despite larger particle sizes is an important reason to regard the revised method as an improvement over its predecessor. Also, Q_{abs} curves show that the 15–25 μm particles themselves can now be detected up to three times more accurately using 811 cm^{-1}.

3. Significance of Improved Detection of Larger Particles

[8] A further question relates to the significance of increasing size detection beyond 20 or 25 μm particles, even if the range of detectable values is increased only by a few microns. *Grenfell and Warren* [1999, hereafter GW] showed that a non-spherical particle is best represented not by a sphere of comparable volume or as one of comparable surface area, but by a *collection of spheres* that together preserve the surface area as well as the volume of the crystal being represented. Absorption and scattering, the two principal processes manifest in the spectra, are keenly dependent on volume and surface area respectively. Any attempt to capture one fully, however, diminishes or exaggerates the importance of the other. An equal volume sphere does not adequately present the surface area for scattering that the crystal does, and an equal surface-area sphere presents too large an absorption length to photons impacting the crystal. A cloud of smaller particles that conserves both volume and area, however, is better constrained on both counts. *Mahesh et al.* [2001, Figure 16] found that the cloud radii obtained from spectral analysis of the South Pole observations were comparable to the radii of ice crystals gathered at the station, when the values were computed as the radii of equivalent surface-to-volume-ratio spheres, rather than equivalent-volume or equivalent-area spheres.

[9] Of significant importance to the discussion here is the fact that radius of the sphere by which such representation is made is often much smaller than that of the equal volume or equal area spheres, and that this representation changes slowly with increasing particle size. Figure 3 shows, for a cylinder of assumed basal radius r and length l, the equivalent-sphere radius that would be obtained by Grenfell and Warren's representation. The key thing to note is that so long as the radius and the length do not change equally, the equivalent radius changes more slowly than the average of the two values. Indeed, so long as one of the values remains unchanged at a small value, the equivalent radius is not significantly altered by changes in the other. The more non-spherical the crystal, thus, more advantageously its equiv-

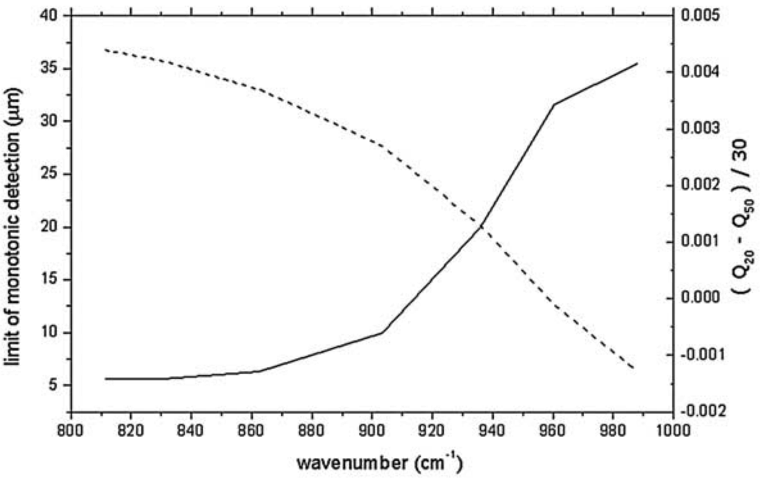

Figure 2. The 'limit of monotonic detection' (left axis, solid line) is the particle radius below which Q_{abs} values rise monotonically; at a particular wavenumber particle sizes below this limit can be detected uniquely. The larger the wavenumber the lower its limit of monotonic detection. Also shown is the spectral variability in Q_{abs} for large particles (right axis, dashed line); the larger the wavenumber, the less suited it is to distinguish between particle sizes greater than 20 μm.

alent radius is captured in the spectra. If crystals grow preferentially along one axis from smaller sizes, then their equivalent radius - as computed by the GW method - grows more slowly. GW representations are appropriate mainly because it is the smaller dimension of a crystal that is important to representing its radiative properties in spectra. As a result, for axes ratios greater than 5 (thin needles) the differences between hexagonal and GW representations are not significant (Thomas Grenfell, personal communication). This is also true for many instances when the aspect ratios are small (less than 0.5).

[10] This suggests that an improvement in the spectral analysis technique to determine only a slightly larger particle size can still be of considerable significance. Even a small increase in the upper boundary of particle size detection (from 25 μm to 35 μm, for example) may permit very many more cloud particle sizes to be determined. For example, from the spectral observations made in 1992 at South Pole station, *Mahesh et al.* obtained cloud particle effective radii for Antarctic plateau clouds over the whole year. They determined that for a fifth of the clouds the particle sizes could be only lower-bounded but not determined, and set a lower bound of 25 μm for the size of such cloud particles. Although particle sizes were determined that were larger than 25 μm, the authors decided these were indistinguishable to a sufficient degree of certainty from much larger particles. Using the improved analysis described here, however, a third of those 'larger' particle sizes can be determined to a similar degree of certainty (Figure 4). More importantly, several of the revised particle sizes were found to be not between 25 and 35 μm, but in fact smaller (between 18 and 25 μm). It appears that the larger wavenumber (988 cm^{-1}) used previously is not merely inadequate to distinguish large particle sizes, but is also less suited to determine slightly smaller particles than 25 μm than 811 cm^{-1}. This result is not surprising; the variation of Q_{abs} with particle size at the higher wavenumber does suggest a lower sensitivity with increasing r_{eff} from values as low as 15 μm.

[11] The 1992 observations were followed by a second field program of measurements at South Pole [*Walden et al.*, 2001]. During this effort spectral data were taken continuously throughout the year, whereas the 1992 observations were made twice daily. The second measurement program was also supported by lidar observations from the Micro-Pulse Lidar Network [*Welton et al.*, 2001], providing accurate cloud heights. A significantly larger amount of spectral data is therefore available for analysis, and the improved particle size detection procedure can be similarly used with the newer observations as well.

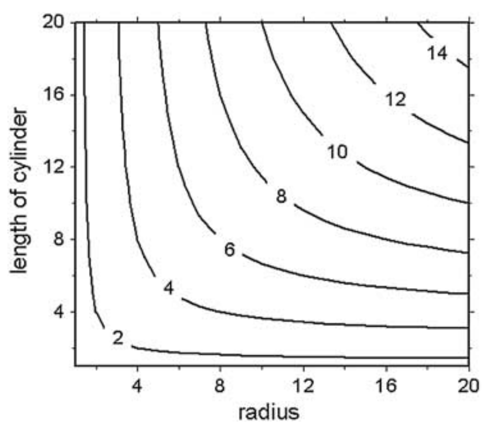

Figure 3. Radii of equivalent volume-surface area-ratio spheres computed for cylinders of varying length and radius. The equivalent radius is more comparable to the smaller of the two dimensions; this suggests that an increased ability to deduce 'equivalent' radii from spectral observations may be significant.

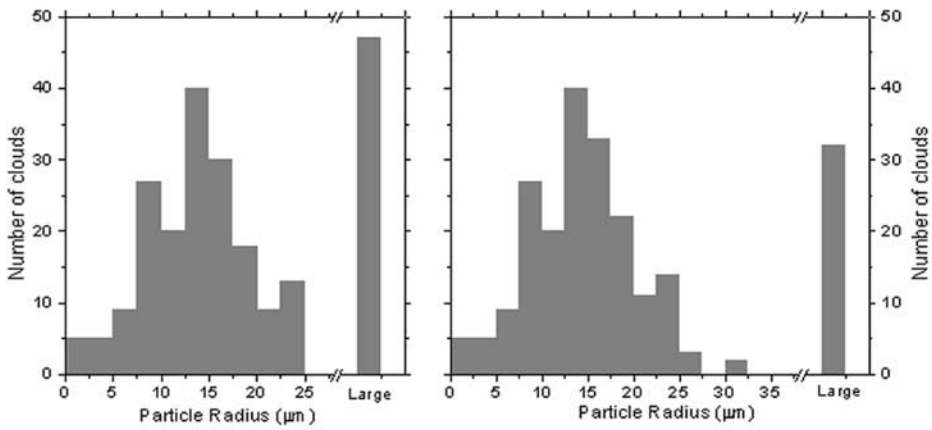

Figure 4. Cloud effective particle radii for Antarctic plateau clouds, obtained from spectral observations taken throughout 1992. The distribution of sizes obtained from an earlier study (left, reproduced from *Mahesh et al.* [2001]) is compared to the improved analysis in this paper (right), which permits the detection of slightly larger particles, and also the more accurate determination of sizes between 17 and 25 μm.

[12] The technique outlined here - to first determine a boundary to particle size using one set of wavenumbers, and thereafter use better-suited wavenumbers to determine the effective radius more accurately - relies on the large variability in the absorption properties of ice in the infrared atmospheric window between 9.6 and 15 μm. Spectral observations of cirrus clouds at other wavelengths could conceivably be used in a similar manner. Newer spectral instruments can make measurements beyond the range of the interferometers used at South Pole, and other spectral intervals (between 3.7–4 μm or 18–25 μm, for example) may be appropriate for similar analysis, provided two critical conditions are met. First, the spectral intervals must include significant variability in the absorption properties of ice at different particle sizes. And second, in any set of spectral micro-windows used for analysis, the selected wavenumbers must be close enough together that uncertainties in radiance observations are closely correlated from one wavenumber to another, thereby reducing their influence on the analysis technique. The use of other, more widely separated wavenumbers, or of spectral intervals where absorption properties of ice are not sufficiently varied, will limit the advantage seen in this spectral window.

4. Conclusions

[13] Infrared spectra from ice clouds can be analyzed to obtain particle effective radii by exploiting the dependence of ice absorption efficiency on wavenumber as well as particle size. The availability of high-spectral observations from recent years has increased the number of channels from which the wavenumbers best suited to such analysis can be selected. Despite this, particle radii larger than 20 μm have not been reliably determined, because absorption efficiency is typically unchanging beyond this size at most wavenumbers. Also, at wavenumbers where there is sensitivity to larger particles, absorption efficiencies are not unique. These two limitations, however, are not simultaneously manifest at the same wavenumbers. Therefore, by using one set of wavenumbers to differentiate between small and large particles, and a second set to determine the actual sizes, effective particle radii up to 30–35 microns can be determined. In this paper, the usefulness of this improved analysis is demonstrated using spectral observations made from the ground at South Pole station in 1992. Also, because the effective particle radius manifest in the cloud spectra typically changes more slowly the axes lengths of the particles themselves, this gain is especially significant. Increasing the boundary of detection capability by 10 microns can result in reliable size determinations in a significant number of cirrus clouds. This is demonstrated for the 1992 Antarctic observations; where previously only a lower bound to particle size was known, now a third of the previously undetermined cloud particle radii are found.

[14] This technique can be used with more extensive data now available from the Antarctic plateau, as well as in other observations of cirrus clouds. A similar analysis using aircraft-based data will help assess the usefulness of this improvement in the downward-looking case as well. Clearly, the selective use of wavenumbers most suited to study clouds of a particular size can provide significant gains. The routine application of such methods to high-resolution spectral data - both currently available and expected from future satellite missions - is recommended.

[15] **Acknowledgments.** The National Aeronautics and Space Administration (NASA) Earth Observing System program, and the NASA Sensor Intercomparison and Merger fund for Biological and Interdisciplinary Oceanic Studies funded this research. The author thanks Thomas Grenfell and Daniel DeSlover for helpful discussions.

References

Grenfell, T. C., and S. G. Warren (1999), Representation of a nonspherical ice particle by a collection of independent spheres for scattering and absorption of radiation, *J. Geophys. Res.*, *104*(D24), 31,697–31,710.

King, M. D., Y. J. Kaufman, W. P. Menzel, and D. Tanré (1992), Remote Sensing of Cloud, Aerosol, and Water Vapor Properties from the Moderate Resolution Imaging Spectrometer (MODIS), *IEEE Trans. Geosci. Remote Sens.*, *30*, 1–27.

Mahesh, A., V. P. Walden, and S. G. Warren (2001), Ground-based infrared remote sensing of cloud properties over the Antarctic Plateau: Part II: Cloud optical depths and particle sizes, *J. Appl. Meteorol.*, *40*, 1279–1294.

Perovich, D., E. L. Andreas, J. A. Curry, H. Eiken, C. W. Fairall, T. C. Grenfell, P. S. Guest, J. Intrieri, D. Kadko, R. W. Lindsay, M. G. McPhee, J. Morison, R. E. Moritz, C. A. Paulson, W. S. Pegau, P. O. G. Persson,

R. Pinkel, J. A. Richter-Menge, T. Stanton, H. Stern, M. Sturm, W. B. Tucker III, and T. Uttal (1999), Year on Ice Gives Climate Insights, *EOS Tran. AGU*, *80*(41), 481–486.

Walden, V. P., S. G. Warren, J. D. Spinhirne, A. Heymsfield, R. E. Brandt, P. Rowe, M. S. Town, S. Hudson, and R. M. Jones (2001), The South Pole Atmospheric Radiation and Cloud Lidar Experiment (SPARCLE), in *Sixth Conference on Polar Meteorology and Oceanography*, pp. 297–299, American Meteorological Society, Boston.

Walden, V. P., S. G. Warren, and F. J. Murcray (1998), Measurements of the downward longwave radiation spectrum over the Antarctic Plateau, and comparisons with a line-by-line radiative transfer model for clear skies, *J. Geophys. Res.*, *103*(D4), 3825–3846.

Welton, E. J., J. R. Campbell, J. D. Spinhirne, and V. S. Scott (2001), Global monitoring of clouds and aerosols using a network of micro-pulse lidar systems, in *Lidar Remote Sensing for Industry and Environmental Monitoring*, edited by U. N. Singh, T. Itabe, and N. Sugimoto, *Proc. SPIE*, *4153*, 151–158.

Zak, B. D., and K. Stamnes (1992), The North Slope of Alaska: The Atmospheric Radiation Measurement Program's Window on High Latitude Phenomena, in *Proceedings of the Second Atmospheric Radiation Measurement (ARM) (Science) Team Meeting, CONF-9110336*, US Dept. of Energy, Washington, D. C.

A. Mahesh, NASA, Goddard Space Flight Center, Greenbelt, MD 20771, USA. (mahesh@agnes.gsfc.nasa.gov)